A NOVEL HYBRID FORWARD OSMOSIS-NANOFILTRATION TECHNOLOGY FOR SEAWATER DESALINATION

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SUMMARY

Reverse osmosis (RO) is the leading technology used for seawater desalination. It is effective in water reclamation but requires a large amount of pumping energy. This project aims to develop a novel hybrid forward osmosis (FO) - nanofiltraton (NF) technology for seawater desalination which lowers the energy requirement for seawater desalination. A dual salt technology was proposed for the FO process, with the combinations of firstly, sodium sulfate and magnesium sulfate, secondly, magnesium chloride and magnesium sulfate. From our results, the combination of magnesium chloride and magnesium sulfate (1:1 proportion) yielded better water flux than sodium sulfate and magnesium sulfate.

ABSTRACT

Currently, the reverse osmosis process (RO) is one of the main technologies used for seawater desalination. It is effective in water reclamation but requires a large amount of pumping energy. Hence, there is a need to develop novel technology to lower the energy requirement for seawater desalination. The aim of this project is to develop a novel hybrid forward osmosis (FO) - nanofiltraton (NF) technology for seawater desalination. The FO process relies on the concentration difference between two solutions as a driving force to transport water across a semi-permeable membrane. It can remove all other salts and impurities of seawater, and the permeate water contains only a single solute. Nanofiltration (NF) will then be used to obtain clean water and recycle the solute for use in the FO process. In this project, a dual salt technology was proposed for the FO process, with the combinations of firstly, sodium sulfate and magnesium sulfate, secondly, magnesium chloride and magnesium sulfate. We tested the dual salts in different proportions and concentrations to investigate the optimal operating parameters for both FO and NF combined. From the results obtained, the combination of magnesium chloride and magnesium sulfate yielded better water flux than sodium sulfate and magnesium sulfate. The magnesium chloride-magnesium sulfate (1:3) obtained better flux and rejection in NF while 3:1 excelled in FO. Hence, it was concluded that the 1:1 was the optimum proportion.

BACKGROUND AND PURPOSE OF RESEARCH AREA

Membrane processes, particularly reverse osmosis (RO) is currently one of the most successful technology for water reclamation and seawater desalination. However, with the increasing cost of energy, further reduction in energy consumption is desirable. Recently, the forward osmosis (FO) process is being actively studied by various researchers as an alternative membrane technology for water reclamation due to its low energy requirement and high water recovery.

The FO process requires a draw solution that has a higher osmotic pressure than the feed solution. It utilizes an osmotic pressure gradient across a highly-selective membrane, such that only water can permeate from the feed solution through the membrane via osmosis to the draw solution. Various draw solutions at high concentration can have exceedingly large osmotic pressure, which may potentially lead to a much higher water flux and recoveries as compared to the more expensive RO which utilizes hydraulic pressure.

The experimental set-up below as depicted in Fig 1 desalinates sea water (feed solution) to produce clean product water. The set-up consists of a forward osmosis (FO) module and a nanofiltration (NF) module. Water molecules from the feed solution pass through the membrane via osmosis into the draw solution due to the difference in osmotic pressure of the two solutions, while the salt in the feed solution is retained. Draw solutes which have high osmotic pressure can be used in the draw solution. Subsequent to the FO module is the NF module that is used to reconcentrate the diluted draw solution to be reused as the concentrated draw solution for the FO module. At the same time, the NF module, which makes use of hydraulic pressure (about 50% of the pumping energy used in RO), is capable of rejecting more than 98% of many different draw solutes to produce clean product water for human consumption and other usages.

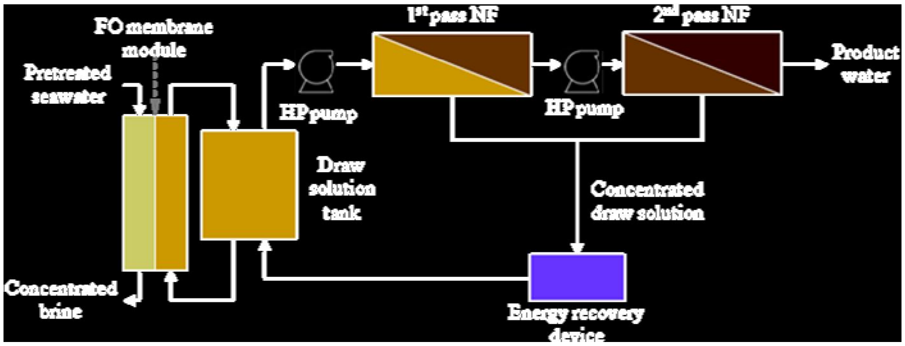

Fig 1: Schematic diagram of the FO-NF hybrid experimental Set-up (software: Microsoft Word 2003)

The study on the use of the FO process first started in 1965. Batchelder [1] used the FO process for the desalination of seawater. Following which, several scientists including Glew [2], Frank [3] and Kravath [4] utilized a number of different draw solutions. Most notably, Stache [5] pioneered the use of the FO process to design an osmotic bag to produce a drinkable water source from seawater for emergency use. The key design for the osmotic bag is being currently adopted by Hydration Technologies Inc. for the commercial production of osmotic water bag that can be used for many purposes.

The central issues that had remained unsolved up till now are that the water production rate per membrane area (water flux) for the FO process is still relatively lower than other membrane processes, and that the draw solutes were diluted sufficiently for direct consumption and no ideal draw solutes can be removed from the draw solutions to produce clean product water. Consequently, future studies on the FO process involve investigations that permit the use of the FO process for large-scale production of clean water.

Currently, the leading scientists on FO research are Professor Elimelech's group at the Yale University and Professor Ng's group at the National University of Singapore. McCutcheon et al. [6] presented a novel ammonia-carbon dioxide FO process for seawater desalination and a pilot plant was set up [7]. FO process had also been developed by

Holloway et al. [8] for the concentration of anaerobic digester concentrate with much success. It is also currently being used in the FO/RO process for landfill leachate treatment [9]. FO process is also actively being used as a process for the direct osmotic concentration of liquid food [10]. Tang et al. [11] proposed the use of the FO process for brine concentration for brine disposal, which is critical for inland desalination.

HYPOTHESIS OF RESEARCH

In this project, a dual-salt draw solution was hypothesized to replace a single salt draw solute in the hybrid FO-NF process. It is predicted that a dual salt draw solution will perform better than a single salt draw solute in terms of achieving a higher water flux in FO and salt rejection in NF. The hybrid FO-NF system is expected to desalinate seawater to produce drinking water that meets the WHO conductivity guideline for drinking water.

MATERIALS AND METHODS

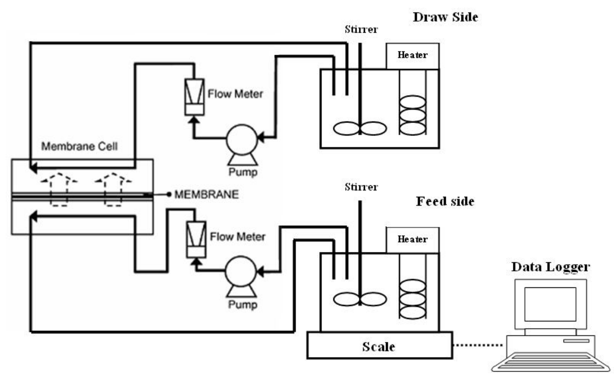

Fig 2: Schematic diagram of the Forward osmosis experimental Set-up (software: Microsoft Word 2003)

The schematic diagram of the FO experimental set-up as shown in Fig 2 above depicts the first apparatus used in this study. The heater is used to maintain a constant temperature of the solutions throughout the experiment. The stirrer ensures that the solutions are homogenous and the pump keeps a constant cross flow rate across the membrane. The scale which is connected to the data logger is used to measure the change in mass of the feed solution to calculate the water flux, which is given in cubic meter per square meter of membrane per second (m/s) or gallons per square feet per day (GFD).

The feed solution that is used is either deionized Na_2SO_4-$MgSO_4$ or $MgCl_2$-$MgSO_4$. The concentration of the dual salts used ranges from 40g/L to 120g/L. The FO membrane (Hydration Technologies Inc., Albany, OR) used is made from cellulose acetate and is highly hydrophilic. It consists of a woven support mesh embedded within the membrane.

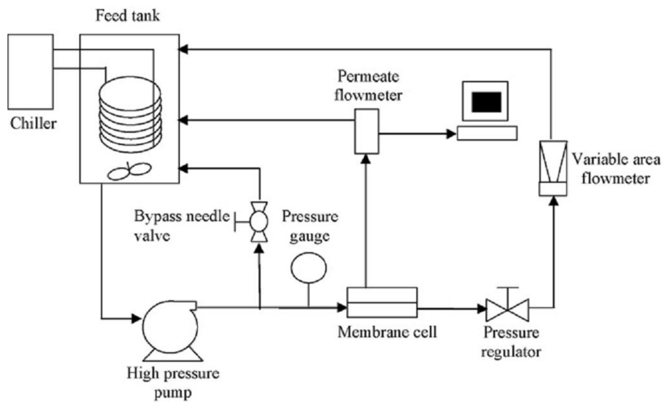

Fig 3: Schematic diagram of the Nano-filtration experimental Set-up (software: Microsoft Word 2003)

The second part of our experiment consists of the NF set up as shown in Fig 3. The NF set up consists of the feed solution tank, a cooler, the NF membrane cell. The feed solution tank stores the diluted draw solution from the FO process. The feed solution passes through the NF membrane cell which consists of the NF membrane in reverse mode (dense layer facing feed solution).

The feed solutions, namely Na_2SO_4-$MgSO_4$ and $MgCl_2$-$MgSO_4$ were tested in different dilution range from 40g/L to 120g/L to compare the water flux and solute rejection.

RESULTS AND DISCUSSION

Selection of dual-salts

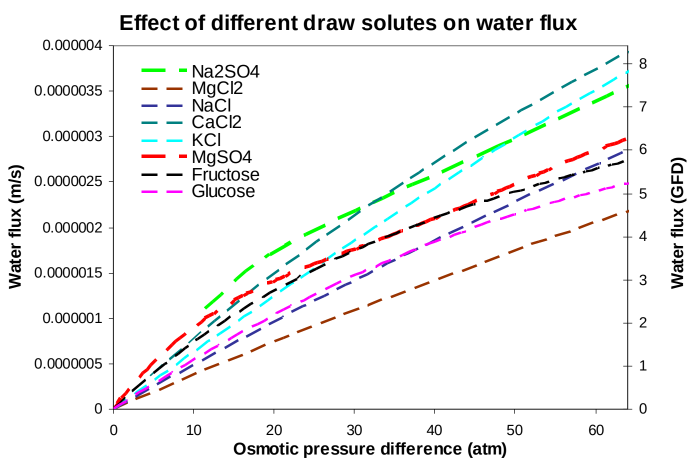

Fig 4: Graph of different draw solutes against water flux in FO (software: Microsoft Excel 2003)

Fig 4 shows the effect of different draw solutes on the water flux obtained during FO. It was observed that $MgSO_4$ produced a high water flux and high solute rejection in the FO process. In order to obtain the most desirable water flux and solute rejection, a combination of solutes to obtain a high water flux and high solute rejection in both the FO and NF process must be achieved. Comparing the results with the other solutes, Na_2SO_4 and $MgCl_2$ was shortlisted as well. Solutes with divalent ions (SO_4^{2-}, Mg^{2+}) are predicted to have higher rejection and since the water flux achieved is relatively high, they are the 2 most promising draw solutes to complement $MgSO_4$ to make up dual-salts draw solution.

Effect of draw solute concentration on water flux for FO

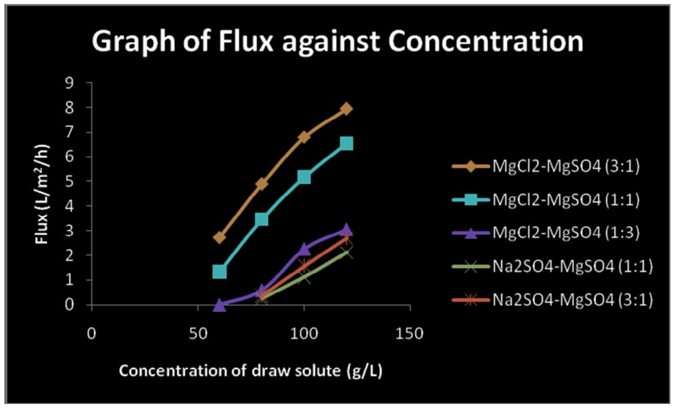

Fig 5: Graph of water flux against concentration of draw solute in FO (software: Microsoft Excel 2003)

From Fig 5, $MgCl_2$-$MgSO_4$ (3:1) and $MgCl_2$-$MgSO_4$ (1:1) achieved the top 2 highest water flux among the 5 dual-salts draw solutes during FO. The water flux achieved by $MgCl_2$-$MgSO_4$ (3:1) was more than 2 times and the water flux achieved by $MgCl_2$-$MgSO_4$ (1:1) was approximately 2 times that achieved by the remaining three draw solutes. As the concentration of the draw solute increases, the concentration gradient between the feed and draw solution becomes steeper and increases the driving force, hence the water flux obtained during FO increases proportionately.

Na_2SO_4-$MgSO_4$ combination yielded a very low water flux which made it an infeasible component of the dual-salt draw solute. The $MgCl_2$-$MgSO_4$ combination showed more potential to be the more ideal draw solute due to its much better performance in the FO process.

Effect of feed solution concentration on water flux for NF

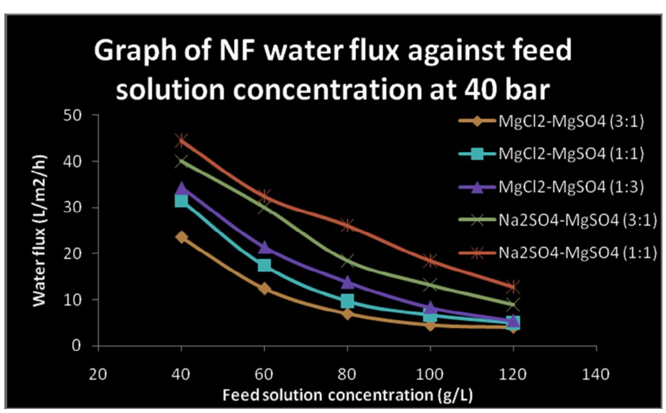

Fig 6: Graph of NF water flux against feed solution concentration at 40 bar (software: Microsoft Excel 2003)

It is theorized that the concentration of the feed solution used in the NF process can affect the water flux. Fig 6 shows the effect of the feed solution concentration on the water flux. It can be observed that as the concentration of the feed solution increased from 40g/L to 120g/L, the water flux decreased proportionately. Therefore it can be concluded that a lower concentration of the feed solution would result in a higher water flux and vice versa. This is because when the diluted draw solution from the FO process enters the NF process, it generates an opposing osmotic pressure. In the graph in Fig 6, we considered the results for the different NF feed solutions at a pressure of 40 bar. A higher concentration of the feed solution would result in a high osmotic pressure, which effectively reduces the overall driving force of the NF process. Hence, the water flux is lower when the solution concentration is higher.

Fig 6 shows that as the proportion of $MgCl_2$ increases, the water flux achieved in FO increases while the water flux achieved in NF decreases. On the other hand, as the proportion of $MgSO_4$ increases, the water flux achieved in FO decreases while the water flux achieved in NF increases. Hence, in order to ensure relatively good performance for both FO and NF, the proposed feed solution proportion is $MgCl_2$-$MgSO_4$ (1:1).

Effect of feed solution concentration on solute rejection for NF

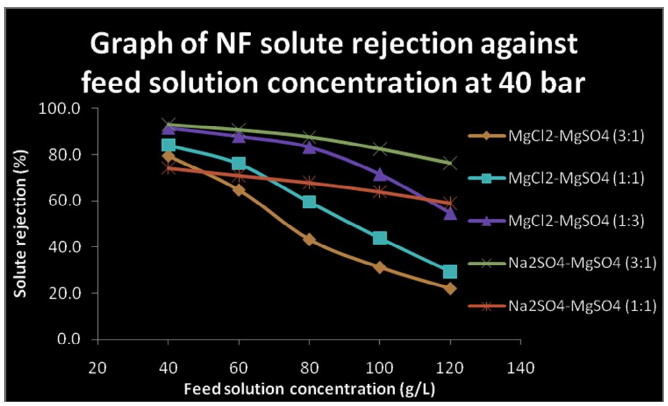

Fig 7: Graph of NF solute rejection against feed solution concentration at 40 bar (software: Microsoft Excel 2003)

Fig 7 shows the effect of the feed solution concentration on the NF solute rejection at a constant pressure of 40 bar. As the feed solution concentration increases from 40g/L to 120g/L, the NF solute rejection decreased proportionately. As the feed solution becomes more concentrated, the proportion of solute present increases and hence decreasing the NF solute rejection. Generally, the rejection ranges between 25% to 95% for both dual-salt draw solutes. However, due to advances in research and development, the performance of NF membranes has improved tremendously in recent years and is expected to continue doing so in the future. Hence, it is realistic to expect to maintain the NF solute rejection above 80% to 90%.

Effect of pressure on water flux for NF

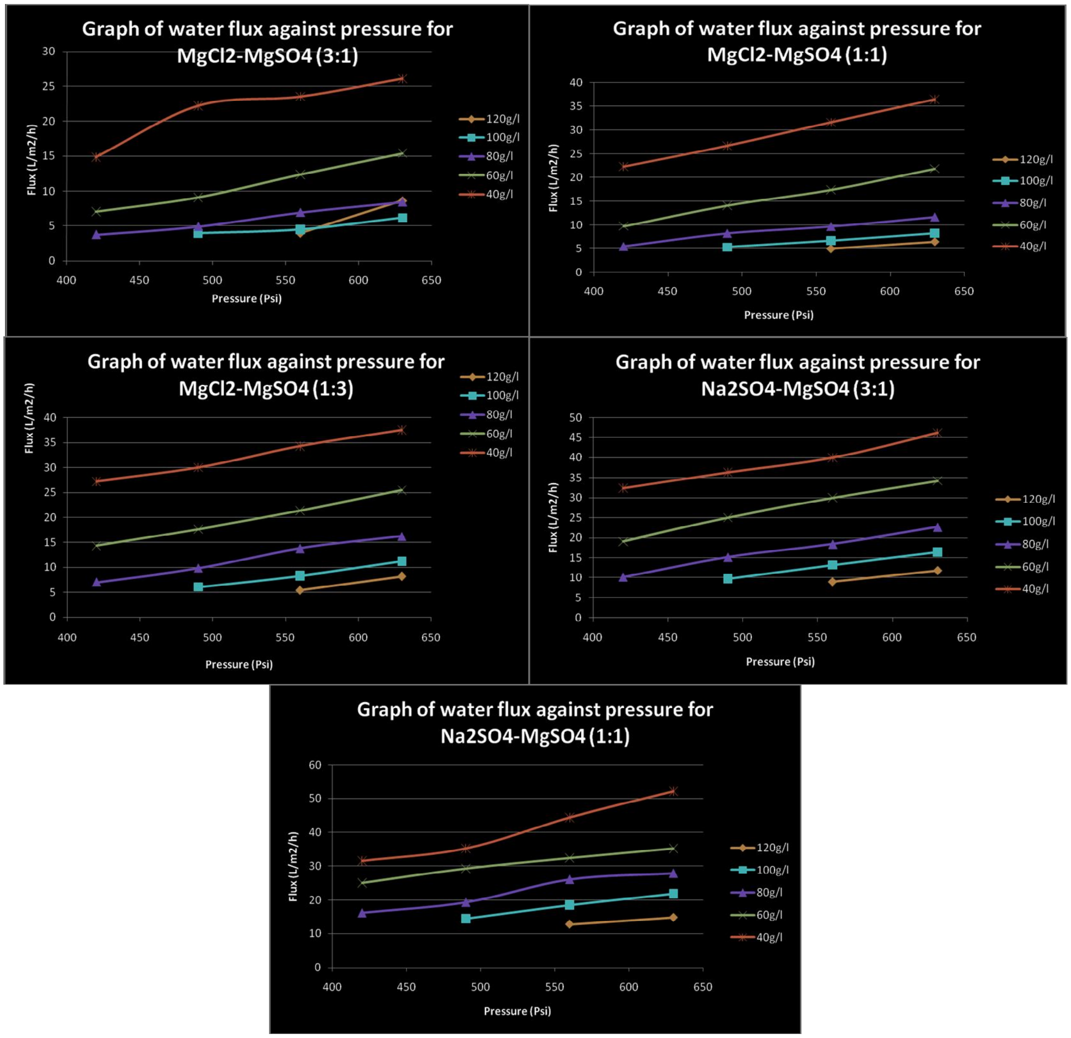

Fig 8: Graph of water flux against pressure for 8.1: $MgCl_2$-$MgSO_4$ (3:1); 8.2: $MgCl_2$-$MgSO_4$ (1:1); 8.3: $MgCl_2$-$MgSO_4$ (1:3); 8.4: Na_2SO_4-$MgSO_4$ (3:1); 8.5: Na_2SO_4-$MgSO_4$ (1:1) (software: Microsoft Excel 2003)

Fig 8.1 to Fig 8.5 show the effect of the pressure of the system on the water flux obtained during NF. The 5 graphs observed similar trends that displayed that as pressure increases, a higher driving force results in a higher water flux obtained. To ensure the efficiency of the system, the water flux should be kept above 5 LMH. Hence, a recommended pressure for the system to be subjected to during first pass NF is 600 Psi or 40 bars and above.

Prediction and comparison of water quality

Fig 9: Table for prediction and comparison of water quality.(Software: Microsoft Word 2003)

Dual-salts Draw Solute	Salt Ratio	Draw Solution Concentration (g/L)	1st Pass Permeate Conductivity (µs/cm)	2nd Pass Permeate Conductivity (µs/cm)	WHO Conductivity Guideline (µs/cm)
$MgCl_2$-$MgSO_4$	3:1	120	62640	626	500
$MgCl_2$-$MgSO_4$	1:3	120	16350	164	
$MgCl_2$-$MgSO_4$	1:1	120	27400	274	
Na_2SO_4-$MgSO_4$	3:1	120	9405	94.1	
Na_2SO_4-$MgSO_4$	1:1	120	18760	188	

Fig 9 shows the predicted conductivity values of the first and second pass permeates in NF for the two dual-salts draw solutes in different proportions. It also provides a comparison of water quality with the current World Health Organization (WHO) drinking water conductivity guidelines. It is observed that all 2nd –pass permeates produced by the 2-pass NF re-concentration scheme, with the exception of $MgCl_2$-$MgSO_4$ (3:1), has conductivity values less than the WHO conductivity guideline of 500 us/cm. The lowest conductivity achieved is 94.1 us/cm yielded by Na_2SO_4-$MgSO_4$ (1:1). Based on our selection of $MgCl_2$-$MgSO_4$ (1:1) as the optimal dual-salts draw solution, the attained conductivity of 274µs/cm is comparable to that of tap water.

CONCLUSION

The FO-NF process is a recyclable process with a low energy requirement and high salt rejection. A dual-salt draw solute is recommended to achieve high water flux in FO water flux and salt rejection in NF. The FO-NF process is a promising alternative technology for seawater desalination to produce drinkable product water that meets the WHO drinking water guidelines. The combination of magnesium chloride and magnesium sulfate yielded better water flux than sodium sulfate and magnesium sulfate. The magnesium chloride-magnesium sulfate (1:3) obtained better flux and rejection in NF while 3:1 excelled in FO. Hence, it was concluded that the 1:1 was the optimum proportion. Additional improvements can be made by optimizing the concentration of the draw solution to obtain a reasonably high water flux. Another aspect will be to investigate membrane performance in terms of flux and rejection. Implications include the possibility of scaling due to the high concentration of draw solutes used, causing inorganic fouling on both the FO and NF membranes.

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